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Assessing sustainable groundwater abstraction: an evaluation of impacts on groundwater quantity and quality

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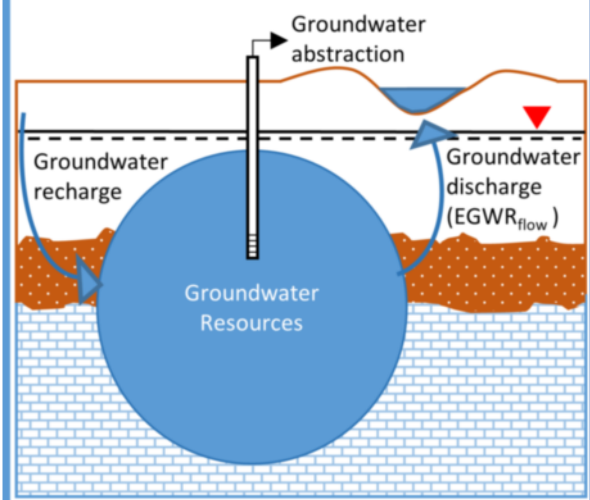
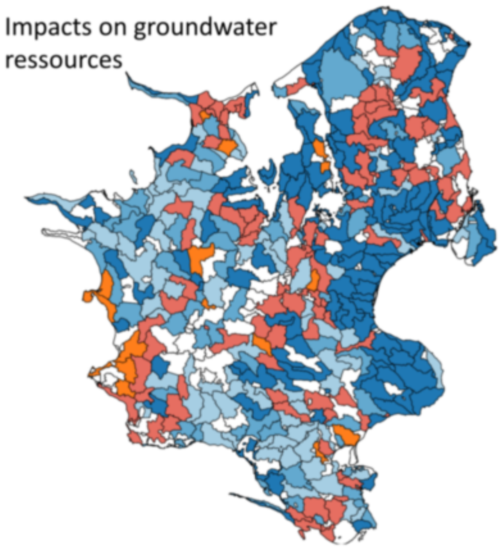


Ryle Nørskov Gejl

PhD Thesis
September 2019



DTU Environment
Department of Environmental Engineering

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The synopsis part of this thesis is available as a PDF file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk.

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Preface

This thesis is an industrial PhD conducted partly at the Technical University of Denmark, DTU, and partly at Copenhagen's water utility, HOFOR.

It is organised in two parts: the first puts into context the findings of the PhD in an introductive review, while the second part consists of the papers listed below. These will be referred to in the text by their paper number, written in the Roman numerals **I-III**.

I Gejl, R.N., Bjerg, P.L., Henriksen, H.J., Hauschild, M.Z., Rasmussen, J., Rygaard, M., 2018. Integrating groundwater stress in life-cycle assessments – An evaluation of water abstraction. J. Environ. Manage. 222. https://doi.org/10.1016/j.jenvman.2018.05.058

II Gejl, R.N., Rygaard, M., Henriksen, H.J., Rasmussen, J., Bjerg, P.L., 2019. Understanding the impacts of groundwater abstraction through long-term trends in water quality. Water Res. 241–251.

III Gejl, R.N., Bjerg, P.L., Bitsch, K., Troldborg, L., Schullehner, J., Henriksen, H.J., Rasmussen, J., Rygaard, M., (2019). Relating wellfield drawdown and water quality to aquifer sustainability – a method for assessing safe groundwater abstraction. Ecological indicators. Submitted.

In this online version of the thesis, paper **I-III** are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljoevej, Building 113, 2800 Kgs. Lyngby, Denmark, info@env.dtu.dk.

Dissemination of results at international and Danish conferences resulted in contributions to the following conference proceedings (not publicly available):

a) Gejl, R. N.; Bjerg, P. L.; Godskesen, B., Hybel, A.-M.; Rasmussen, J. Rygaard, M. (2015). Betydningen af den geografiske skala for opgørelsen af ferskvandspåvirkning - Vandforsyningens Vandfodspor. Dansk vand konference (DANVA). November 17 – 18. Århus, Denmark. Oral presentation.

b) Gejl, R. N.; Bjerg, P. L.; Godskesen, B., Hybel, A.-M.; Rasmussen, J. Rygaard, M. (2015). Water Supply Water Footprint: How the scale impacts the assessment. Proceedings DTU's Sustain Conference, December 17, Kgs. Lyngby, Denmark. Oral presentation.

c) Gejl, R.N., Bjerg, P.L., Rasmussen, J. & Rygaard, M. (2016). Integration of freshwater impact in lifecycle assessment of three water technologies. 22nd SETAC Europe LCA Case Study Symposium. September 20 – 22, Montpellier, France. Oral Presention.

d) Gejl, R.N., Bjerg, P.L., Rasmussen, J. & Rygaard, M., (2016). Integrering af ferskvandpåvirkninger i livscyklusvurdering af tre vandteknologier. Dansk vand konference (DANVA). November 8 – 9, Århus, Denmark, Oral presentation.

e) Gejl, R.N., Bjerg, P.L., Rasmussen, J. & Rygaard, M. (2017). A local freshwater impact – developing on the *AWaRe* indicator. 9th biennial conference of the International Society for Industrial Ecology (ISIE) and the 25th annual conference of the International Symposium on Sustainable Systems and Technology (ISSST). June 25 – 29, Chicago, United States. Oral presentation.

f) Gejl, R.N., Bjerg, P.L., Rasmussen, J. & Rygaard, M. (2017). Understanding groundwater stress by developing a local impact assessment method. 4th Water Research Conference: The Role of Water Technology Innovation in the Blue Economy, 10 - 13 September, Waterloo, Canada. Poster presentation.

g) Gejl, R.N., Bjerg, P.L., Rasmussen, J. & Rygaard, M. (2018). Proposing the groundwater indicator *AGWaRe*. Vintermøde om jord og grundvandsforurening (ATV- Vintermøde), March 6 – 7, Vejle, Denmark. Poster presentation.

h) Gejl, R. N., Bjerg, P. L., Henriksen, H. J., Troldborg, L., Rasmussen, J. and Rygaard, M. (2018). Improved indicators for assessing aquifer sustainability. Proceedings Nordic Drinking Water Conference (NORDIWA). June 11-13, Oslo, Norway. Oral presentation.

Acknowledgements

This study is conducted at the Department of Environmental Engineering at Technical University of Denmark in collaboration with Hovedstadsområdets Forsyningsselskab, HOFOR, VandCenter Syd and Aarhus Vand. The work is part of an industrial PhD program, funded by the utility partners and Innovation Fund Denmark.

First, I would like to thank my main supervisor Martin Rygaard, who has guided me through this Ph.D. project. Martin is a kind person, who impresses with his in-depth feedback, dedication and constructive approach. He always takes the discussions on the terms of the draft in front of him. Complimentary, is my other supervisor Poul L. Bjerg, who always asks the ontological questions and challenges me on a broader perspective. Together they make a very good team who supports, questions and guides a process and I would not be where I am now, without any of these people. I also want to thank my other three co-supervisors, Jens Rasmussen, Hans Jørgen Henriksen and Michael Zwicky Hauschild. I feel lucky to have such a strong group of experts in water utilities, groundwater impact and LCA sharing their knowledge with me. Their input was crucial for the findings and results of this project.

This project have given me the chance to work both at HOFOR and DTU and I am grateful for both these places to take me in and make me feel welcome. I want to thank the team of Water Resources at HOFOR, where everyone have been sweet and supportive. Especially I want to thank Kristian Bitsch who have helped me with the modelling and his insights and detail-oriented approach. It has been inspirational to work with and around ambitious and dedicated people. From DTU I want to thank Sara Lehrer, Sille Lyster Larsen, Luca Locatelli, Roland Löwe and Sarah Brudler, who have shared more than their professional life with me. Furthermore, I want to thank external collaborators Jörg Schullehner and Lars Troldborg for sharing data and knowledge with me and challenging the findings. In addition, the collaborators in TreVand Troels Kærgaard Bjerre from VandCenter Syd and Bo Vægter from Århus Vand have given me a range of utility perspectives and discussed findings for further advancements.

Finally, I would like to thank my circles. I have had some rough years, professionally and personally, and I am very grateful for love and support from partner, friends, family and community. Especially, Lucia, who helps me through, whatever it is.

Summary

Groundwater is often a stable, clean and important drinking water resource, and in many places around the world, it is a prerequisite for economic growth; in fact, 50% of the world's population depends on groundwater. However, bad abstraction management endangers availability and quality, and so in order to ensure future water security, there is a need for trustworthy, reliable and accurate assessment methods to identify the impacts on groundwater resources. Internationally, there are good indicators for evaluating general water stress on a large scale, but with ever-increasing pressure on companies to evaluate and communicate their environmental footprint, water utilities also need tools to evaluate groundwater stress on a local scale.

This PhD project proposes new indicators for evaluation of local impacts on groundwater abstraction. Secondly, it explores the relationship between groundwater drawdown and water quality. Finally, it develops a new method for integrating considerations of groundwater quality into an assessment of sustainable groundwater abstraction.

This thesis discusses current indicators, their challenges, and potential solutions. One of the indicators proposed, *AGWaRe,* which evaluates **A**vailable **G**round**Wa**ter **Re**maining for other users, is based on the principles of an existing and internationally accepted indicator, *AWaRe*. *AGWaRe* is developed so that it can evaluate groundwater and be applied on a local scale. *AGWaRe* and other indicators include environmental groundwater requirement (*EGWRs*), recognizing that water abstraction affects ecosystems. Generally, *EGWRs,* and thereby existing indicators, are based on evaluating quantitative changes to stream flows and aquifer recharge, and they do not take into consideration the effect on water quality caused by abstraction. To evaluate how groundwater abstraction affects groundwater quality, the correlation between drawdown and water quality was analysed based on data from 1900 – 2014 for 28 well fields supplying water to Copenhagen. It showed that for these well fields the development in sulphate concentrations can indicate overall sustainable groundwater abstraction. Changes in sulphate concentrations indicated that the water abstraction in the 1980s, when it was at its highest, was unsustainable, because sulphate concentrations were increasing steadily. The results highlight that groundwater abstraction has generally been sustainable at these well fields since the 1990s, because sulphate concentrations have been overall stable or decreased slightly. Recognizing that there is a limit to how much water can be abstracted from groundwater aquifers, if neither

streamflow nor groundwater quality should be changed in an unacceptably degree, the following definition for *EGWRs* is proposed "*water from groundwater resources needed to sustain flows, preserve groundwater dependent ecosystems and maintain good groundwater quality*". Hence, it is suggested to divide *EGWRs* in two categories, 1) $EGWR_{flow}$, which is groundwater reserved to sustain base flow in streams and groundwater-dependent ecosystems and 2) $EGWR_{wq}$, which is groundwater reserved to sustain water quality affected by water abstraction in the aquifers. The correlation between drawdown and changed water quality was used to model a safe groundwater abstraction for Zealand, Denmark. A conditioned drawdown was applied in the aquifers to secure stable groundwater quality. It showed that there is more groundwater available for abstraction, however the actual abstraction should be redistributed to secure a stable groundwater quality in all aquifers. Hence, it was possible to evaluate a groundwater abstraction for both groundwater quantity and quality. In addition, several suggestions are made in terms of how the utilities and other stakeholders can use and implement the findings in their search for sustainable groundwater abstraction.

Dansk sammenfatning

Grundvand er ofte en stabil, ren og vigtig kilde til drikkevand og mange steder en forudsætning for økonomisk vækst. 50% af befolkningen på verdensplan afhænger af grundvand. Mange steder truer forvaltningen af vandindvinding både grundvandskvantiteten og -kvaliteten. For at sikre den fremtidige vandindvinding er der brug for pålidelige evalueringsmetoder, der kan identificere påvirkninger fra grundvandsindvinding. Internationalt er der relevante metoder til at vurdere overordnet vandstress på stor skala. I takt med en forventning om, at virksomheder skal vurdere og formidle deres miljøpåvirkninger, er der kommet et behov for også at kunne vurdere påvirkningen af grundvandsindvinding på en lokal og mindre skala der er relevant for vandforsyninger.

Dette PhD projekt foreslår nye indikatorer til at evaluere lokale påvirkning af grundvandsindvinding. Dernæst, undersøges sammenhænge mellem afsænkning af vandspejl og ændring i vandkvalitet. Endeligt, udvikles en metode til at inkludere kvalitet i evalueringer af bæredygtig vandindvinding.

Denne afhandling diskuterer nuværende indikatorer, deres udfordringer og deres potentialer. En af de foreslået indikatorer, *AGWaRe,* evaluerer, hvor meget vand der er til rådighed (**A**vailable **G**round**Wa**ter **Re**maining). Indikatoren er baseret på den internationale anerkendte indikator *AWaRe*. *AGWaRe* er udviklet til at være grundvandsspecifik, og til at kunne anvendes på lokal skala. *AGWaRe* og andre indikatorer indeholder en parameter for *grundvandsbehov til miljøet* (*EGWRs*) ud fra erkendelsen af, at grundvandsindvindingen påvirker økosystemer. Generelt fokuserer *EWGR* og dermed mange indikatorer på kvantitative ændringer af flows i vandløb og akviferer, mens der har været mindre fokus på ændringer i vandkvalitet. For at vurdere, hvordan indvinding påvirker grundvandskvaliteten, blev sammenhænge mellem afsænkning i vandspejl og vandkvalitet vurderet ud fra data fra 1900-2014 for 28 kildepladser, der leverer vand til København. Undersøgelsen viste, at udviklingen i sulfatkoncentrationen kan indikere, om indvindingen overordnet er bæredygtig på disse kildepladser. Ændringer i sulfat-koncentrationen indikerede, at grundvandsindvindingen i 1980'erne, hvor den var på sit højeste, var ikke-bæredygtig på grund af stigende sulfatkoncentrationer. Resultaterne viser, at indvindingen generelt var bæredygtig fra 1990'erne, fordi sulfatkoncentrationerne generelt har været stabile eller let faldende. Fra erkendelsen af, at der er en begrænsning for, hvor meget grundvand der kan indvindes, hvis hverken vandløb eller grundvandskvaliteten skal påvirkes i en uacceptabel grad, foreslås følgende definition for *EGWRs: (Environmental groundwater requirements)* ”*vand fra grundvandsressourcer, der er nødvendige til at opretholde*

strømninger, beskytte grundvandsafhængige økosystemer og sikre god grundvandskvalitet". Følgelig, kan *EGWRs* opdeles i to kategorier 1) $EGWR_{flow}$, der repræsenterer grundvand reserveret til at opretholde strømninger i vandløb og grundvandsafhængige økosystemer og 2) $EGWR_{wq}$, der repræsenterer grundvand reserveret til at sikre grundvandskvaliteten, som er afhængig af grundvandsindvinding. Sammenhængen mellem afsænkning og ændret vandkvalitet blev brugt til at modellere en sikker grundvandsindvinding for Sjælland. En betinget afsænkning i akvifererne blev anvendt til at sikre en stabil grundvandskvalitet. Den viste, at der kunne indvindes mere vand, men at det forudsætter en omfordeling, hvis grundvandskvaliteten skal sikres i alle akviferer. Det var muligt at vurdere grundvandsindvindingen baseret på påvirkninger af kvantitet samt kvalitet. Desuden har projektet demonstreret, hvordan vandforsyningerne kan bruge disse indikatorer i deres indsats for at opnå en bæredygtig grundvandsindvinding.

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Abbreviations

AMD	Availability-minus-demand
AGWaRe	Available groundwater remaining
AWaRe	Available water remaining
EGWRs	Environmental groundwater requirements
EWRs	Environmental water requirements
GF	Groundwater footprint
GWR	Groundwater recharge
LCA	Life cycle assessment
WF	Water footprint
WTA	Withdrawal-to-availability
WSI	Water stress indicator
WSI_{index}	Water stress index
WU	Water use
WR	Water recharge

1 Introduction – Evaluating groundwater impacts

1.1. Why is evaluating groundwater abstraction important?

Groundwater is often a clean and reliant resource and is therefore important for drinking water around the world (IWA, 2014); in Europe, it constitutes half of all consumed drinking water (Völker and Borchardt, 2019). It is generated from precipitation through recharge to the subsurface, but it has different characteristics to surface water, for example in terms of quantity and residence time. Groundwater resources are 100 times more voluminous than surface water (lakes and river storage), and generally it has 1,000 times longer residence time than surface water (UNEP, 2008). Furthermore, groundwater renews at a slow rate compared to surface water and has the advantage of being less dependent on seasonal precipitation and variations. It can be seen as a deposit that stores water for use when surface water is seasonal or unfeasible, and this deposit is constantly replenished. If groundwater abstraction does not exceed the rate of replenishment over a long time, there will be a constant resource available for use. With groundwater constituting an important share of drinking water and with long recharge rates, it is important to understand the impacts related to its abstraction, to secure future drinking water supply.

Increased pressure on groundwater resources, due to increased water consumption (Zektser and Everett, 2004), has sparked an interest in evaluating water impacts around the world, albeit often on a large scale (e.g. Boulay et al., 2017; Gleeson et al., 2012b; Merz, 2001). One study shows that overall there is sufficient water for human needs, including agricultural, industrial and domestic water withdrawals (Steffen et al., 2015), which means that with current water use, freshwater is not scarce on a global scale. However, locally, there can be competing water needs between the domestic, agricultural, power systems, industrial and environmental sectors (Pereira-Cardenal et al., 2016; Töpfer, 2003; Vörösmarty et al., 2010). Groundwater availability is not allocated according to need, and in many places around the world, discrepancies are evident in both time and location. For example, in Brazil, 80% of surface flows are in the Amazonas, where just 9% of the population reside (Júnior et al., 2019); consequently, the majority of Brazilians live in areas with poor water availability. There can also be discrepancies in timing throughout a year and between years; for example, in California, rainfall is mainly in the winter, while the need for water and irrigation is mainly in the summer (Deitch et al., 2016). Additionally, there can be large differences between yearly rainfall levels, resulting in frequent droughts. On top of this issue, California experiences excessive groundwater consumption, which has led to devastating impacts (Faunt et al., 2016). As a result of such discrepancies, large constructions for transporting water have been built around the world; for example large aquaducts have been constructed to facilitate short and long term water trading across hundreds of kilometres in California, using groundwater as buffer storage (Stokes-draut et al., 2017). Another example is the South-to-North Water Transfer project in China has a canal that is 1273 km long, with a design flow rate of 350 m^3/s (Cui et al., 2011). Large differences in water availability exist within the nation scale, but also on the global scale between the global north and the global south, but they also prevail on a smaller local scale, for example in the case of Zealand in Denmark, and so the disparity between water availability and increased consumption highlights the importance of evaluating the availability of water resources.

Over the last few decades, researchers have developed matrices to characterise, map and follow water scarcity on a global scale, showing discrepancies between water use and availability. These assessments are the basis for analysing of food security, economic growth and ecological status (e.g. EEA, 2018; ODI, 2017; The World Bank Group, 2016), and so reliable and accurate assessments are required.

Currently, there are a number of indicators for evaluating the impacts of water abstraction, and these are often based on water balance components, such as withdrawal-to-availability (*WTA*) (Alcamo and Henrichs, 2002), water stress indicator (*WSI*) (Smakhtin et al., 2004), etc. However, advances recently made with the water impact indicator **A**vailable-**Wa**ter-**Re**maining, *AWaRe* (Boulay et al., 2017), have not been developed further for groundwater.

Furthermore, international indicators focus on quantitative changes in flow, but groundwater abstraction should be assessed holistically based on the impacts on the groundwater resource itself, along with any effects on surface water quantity and quality and on aquatic ecosystems (European Union, 2000).

Internationally, there are good indicators for evaluating general water stress on a large scale. However, currently, there are no holistic indicators that can assess groundwater impacts on a local scale and which include both water quality and water quantity.

In Denmark, utilities need to evaluate local impacts on groundwater resources. Furthermore, water utilities in Denmark are required to benchmark their performance between themselves, and therefore there is a need for water impact indicators that are applicable on a local scale. This study is based in Denmark, but the outcomes are relevant to other places in the world.

1.2. Defining sustainable groundwater abstraction

It is a complex task to define *sustainable* groundwater abstraction, but in the following, it means any abstraction that does not compromise the needs of other users, including future needs (Brundtland, 1987). In practice, a sustainable groundwater abstraction changes neither the quantity nor the quality of groundwater resources. Furthermore, sustainable groundwater abstraction leaves sufficient amounts of water for ecosystems above ground. However, in reality a groundwater abstraction will always lead to changes. The question, is how much is acceptable?

This PhD focuses on the groundwater resource and works from the perspective that inflows to and outflows from the groundwater resource should be in balance. Without abstraction (pristine conditions), the system is in balance and what flows in equals what flows out and changes in storativity. Some of the groundwater flowing out is used for environmental needs (*EGWRs*). Introducing abstraction will increase the inflow, or groundwater recharge (*GWR*), and decrease *EGWRs*. The hydrological balance also affects the geochemical state of aquifers (Appelo, 1994; Currell et al., 2010; Kinniburgh et al., 1994), and so excessive abstraction can lead to insufficient water in streams and changes in groundwater quality.

1.3. Impacts related to groundwater abstraction

Groundwater abstraction has numerous impacts on the groundwater resource, such as depletion (Hasan et al., 2018; Konikow, 2015), with one severe example being in the central and southern High Plains, USA, where low recharge has resulted in aquifer overexploitation of 330 km^3 groundwater, which was recharged during the past 13,000 years (Scanlon et al., 2012). Most of the major aquifers in the world's arid and semi-arid zones are experiencing rapid rates of groundwater depletion (Famiglietti, 2014), which potentially contribute to sea-level rise (Konikow and Kendy, 2005). Declining water tables are seen around the world as a consequence of groundwater abstraction (Lashkaripour and Ghafoori, 2011; Luczaj et al., 2017; Whittington and Price, 2006), for example in Pakistan, where unplanned groundwater exploitation, through various ill-formed and inappropriate polices, resulted in alarming declines in groundwater levels of up to 75 m between 1980 and 2008 (Khair et al., 2012). Changed stream flow is also a common concern surrounding groundwater abstraction (Bradley et al., 2014; Kirk, S.; Herbert, 2002; Mccallum et al., 2013; Richter et al., 2012), whilst changes in water quality are also a consequence of groundwater abstraction (Andersen et al., 2001; Morris et al., 2003). Finally, in severe cases, groundwater abstraction can result in land subsidence (Guo et al., 2015; Tularam and Krishna, 2009), for example up to 9 m locally in the Central Valley, California, in the early 1980s, leading to historically low groundwater levels and groundwater storage losses (Faunt et al., 2016).

Numerous factors must be considered when determining sustainable groundwater abstraction, for example carbon emissions (Karimi et al., 2012), electricity consumption (Sanjuan-Delmás et al., 2015) and material demands (Faragò et al., 2019). However, this PhD focus on impacts on groundwater resources, since there are already systematic, well-documented and consistent methods for evaluating other environmental impacts (lifecycle assessments).

1.4. Challenges of assessing groundwater impacts

Water impact indicators have a tendency to focus on surface water, which might be due of the following:

- Groundwater is difficult to delineate. Groundwater, surface water and evapotranspiration are integrated and dynamic, which makes it difficult to define clear boundaries. Surface water is easier to delineate as a function of climate, topography and in- and outflows.
- Groundwater is closely integrated with surface water and may be considered a de facto part of the surface water cycle. However, the institutions managing and legislating them are typically not integrated.
- The impacts on groundwater occur on a timescale extending over decades, which makes it difficult to identify stress at specific points in time. On the other hand, stream flows and surface ecosystems are often affected on a shorter timescale.
- It is expensive to obtain good knowledge of our subsurface, which leads to high uncertainties in how groundwater actually flows – and thereby high uncertainty connected to evaluations of groundwater impacts.

It is important to overcome these challenges, because groundwater constitutes a significant source of drinking water, and hence there is a need for reliable information on how to maintain the groundwater resource useful for the future.

1.5. Objective

The aim of this PhD is to assist local planning for sustainable groundwater abstraction, and water utilities in their work towards obtaining reliable, transparent and acceptable groundwater impact indicators. This included advancing existing groundwater impact indicators and challenging the quantification of *EGWRs*. This thesis and associated articles seek to answer the following questions:

- Could a state-of-the-art water impact indicator be advanced to be applicable to groundwater on a local scale?
- How does groundwater abstraction change quality in the long term?
- Can the exploitable groundwater resource be quantified considering groundwater quality?

1.6. Structure of the thesis

This thesis consists of the following chapters:

- Chapter 2 explains water supply in a Danish context.
- Chapter 3 presents the DK-model and its limitations.
- Chapter 4 discusses different groundwater impact indicators.
- Chapter 5 investigates how water abstraction and water quality are connected.
- Chapter 6 deals with the quantification of *EGWRs*.
- Chapter 7 presents suggestions for application.
- Chapter 8 summarises the conclusions of this thesis.
- Chapter 9 outlines future work and perspectives.

2 Water supply in a Danish context

Danish water supply is based on a decentralised supply structure consisting of common utilities and private wells. There are 2,600 common utilities, each supplying more than 10 households (FRI, 2016), and they are owned either by the municipalities (called public utilities) or by cooperatives. Furthermore, there are approximately 50,000 private or non-common water suppliers. Total water abstraction in Denmark is approximately 650 million m^3/year (GEUS, 2017), and out of this figure, the water supply accounts for 360 million m^3/year, mainly from the public water utilities with 97% (FRI, 2016). Out of the 2,600 common water utilities, only 222 produce more than 0.2 million m^3/year of water. Moreover, water use has decreased in Denmark over the last 30 years; for example, it decreased by 40% from a yearly consumption of 63 m^3/person in 1987 to 38 m^3/person in 2017 (DANVA, 2018).

2.1. Water supply for Greater Copenhagen

The papers in this PhD have studied the water supply system on Zealand. The larger utilities account for the majority of water abstraction in Denmark (GEUS, 2017), and they abstract water from well fields that typically consist of multiple wells 'on a string' or in a certain area (Figure 1). On Zealand, the majority of the water is abstracted from limestone aquifers, and water from the wells is pumped to a collection station, from where it goes to a waterworks and is typically treated with aeration and filtration before distribution to consumers.

2.2. Benchmarking

Water utilities acquire abstraction permissions from the municipalities, who in turn have to follow the state's water plans. Laws about sector organisation and economy apply to any utilities producing more than 0.2 million m^3/year. The Danish Competition and Consumer Authority governs the economic frames and sets targets to improve water utility efficiency.

Each year, the Danish Water Supply Association (for the common utilities) publishes a report of statistics and benchmarks for drinking water (DANVA, 2018). Besides benchmarking water costs, the utilities are compared on nutrient discharges from wastewater treatment plants, water losses, numbers of microbiological control tests, rates of renewal for the distribution system, breakages in the pipe system, operating times and, finally, energy consumption and

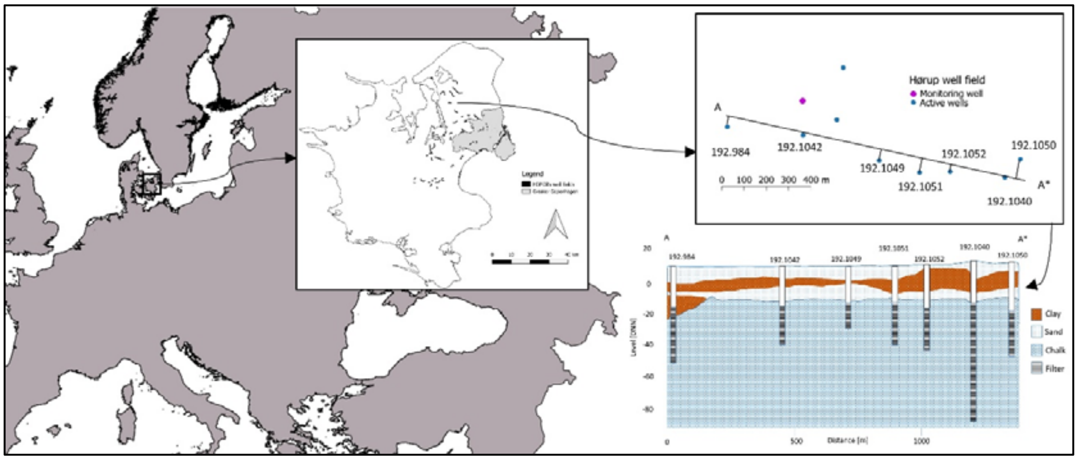

Figure 1: Area of Greater Copenhagen, including HOFOR's well field and a close-up of Hørup as a typical example. A geological profile of some of the wells at Hørup is also provided. Adapted from Gejl et al. (II & III).

production. To date, however, there is little focus on environmental impacts on the resource, water quality and stream flow. Groundwater impacts should be included in benchmarking, to ensure that utilities are compared based on, among others, their impacts related to their main resource use. Furthermore, the possibility of quantifying impacts on the environment can assist water utilities when they need to justify varying water prices between regions; for example, difficult resource conditions may warrant additional costs for water provision.

2.3. River Basin Management Plans

The EU Water Framework Directive is formulated to protect water bodies from the negative impacts of human water use (European Union, 2000), and it is implemented at the national level through the River Basin Management Plans (Naturstyrelsen, 2015). A key focus is holistic water resource management, which involves an integrated assessment of water quantity, quality and physical and ecological conditions. This means that the impacts of groundwater abstraction should be assessed based on the impacts on the groundwater resource itself, along with effects on surface water quantity and quality and on aquatic ecosystems.

3. Hydrological models

Hydrological models are a strong tool for understanding the complexity of groundwater flows and are often used for analysing such resources (e.g. Alcamo et al., 2003; Pastor et al., 2014; Scherer et al., 2015; Schmied et al., 2014).

3.1. DK-model

In Denmark, the national DK-model describes the main parts of the freshwater cycle, such as precipitation, evaporation, surface runoff, groundwater recharge, drainage and groundwater discharge into streams, lakes and the sea (GEUS, 2009; Højberg et al., 2008). The model is designed to evaluate water balance-related questions, for example groundwater resource exploitation, and it can evaluate water balances on the national scale to the catchment scale (Klint et al., 2013). The model is divided into several sub-models, with one sub-model for Zealand, which was used in Gejl et al. (III).

The model uses data from the Danish national geo-database JUPITER (GEUS, 2019), spanning from January 1990 to August 2013 (Højberg et al., 2015). Gejl et al. (III) evaluated for the period January 2003 to December 2012, to avoid misrepresentations of water balances at the beginning of the model period.

The geological model for Zealand is built on a 100 x 100 m grid using layers and lenses for distributing the geological structures, and the calculation layer model is set up on a 500 x 500 m grid (Klint et al., 2013). Model calibration is described in Højberg et al. (2015).

3.2. Limitations of the DK-model

The model calculates the piezometric head for an area rather than a specific point. Furthermore, there are some differences between the numerical and the Theis solution (Figure 2), and therefore we expect some discrepancies between the modelled and observed piezometric head. Additionally, the piezometric head at a given point is complex and can be influenced by local geological structures. Gejl et al (III) observed differences between the modelled and the piezometric head, but it was within the top score for performance criteria when considering the goodness of hydrological models (Henriksen et al., 2003).

Another issue that can lead to discrepancies lies in the fact that the DK-model is based on average abstractions per year, whereas in reality there can be large variations in actual abstractions at a well field.

The early version of the JUPITER database had incorrect data on water abstraction; however, many data have been corrected and the lacking abstraction is evaluated to constitute approximately 24 million m^3 in 2017 (GEUS, 2017).

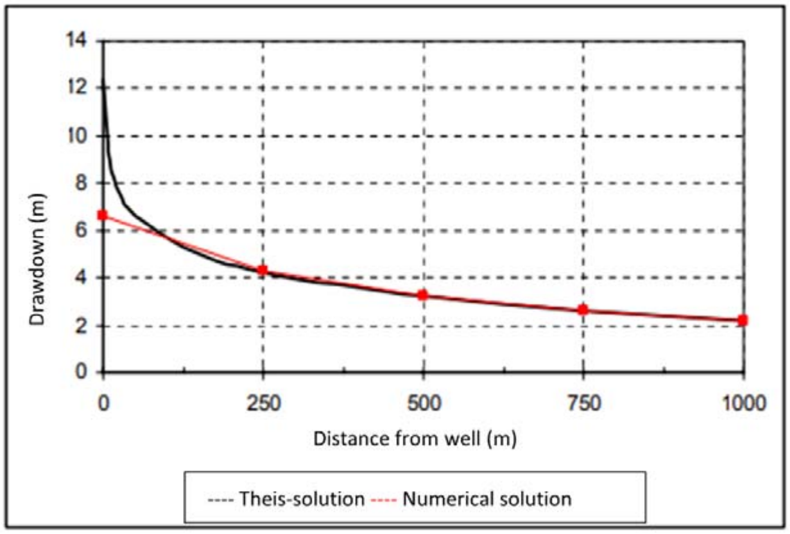

Figure 2: Numerical and modelled drawdown (Sonnenborg and Henriksen, 2005).

Furthermore, the model is designed to handle water balances on a catchment scale (Klint et al., 2013), which means that it cannot be used, for example, to evaluate contamination transport.

4. Groundwater impact indicators

4.1. Existing water impact indicators

Methods for quantifying water impacts have been discussed widely (for example Hoekstra, 2016; Nunez et al., 2016; Pfister et al., 2017). Evaluating impacts from water abstraction is often based on components of the water balance, e.g. withdrawal-to-availability, *WTA* (Alcamo and Henrichs, 2002), Water Stress Indicator (WSI) (Smakhtin et al., 2004), Water Stress Index (WSI_{index}) (Pfister et al., 2009), groundwater footprint (Gleeson et al., 2012b), **A**vailable-**Wa**ter-**Re**maining, *AWaRe* (Boulay et al., 2017) and **A**vailable-**G**round-**Wa**ter-**Re**maining, *AGWaRe* (Gejl et al. (I)) (Table 1). These indicators represent a change in the physical system, for example less water available for other users. Another approach is the water footprint, which is based on a quantification of water needed for a product, including water to grow inputs (blue and green water footprint) and water needed to dilute possible contaminations (grey water footprint) (Hoekstra et al., 2009).

Several of these indicators include environmental water requirements (*EWRs*) to secure water for sustaining flow, maintain wetlands, etc. (International River Foundation, 2007). *EWRs* are based typically on generic definitions of the water balance, with little consideration given to specific ecosystems or geographical differences, and they can therefore contribute to misleading quantifications of impacts.

The abovementioned models have a coarse scale and are usually not calibrated or validated locally, and they will often entail large uncertainties on the local scale. Another implication is that generally these indicators focus on surface water (e.g. Smakhtin et al., 2004) or a combination of surface water and groundwater (e.g. Boulay et al., 2017), which can lead to misrepresentations of groundwater impacts (Gejl et al. (I)).

To overcome the focus on surface water and the large-scale perspective, an indicator to assess groundwater impact, *AGWaRe*, which evaluates the **A**vailable **G**round**Wa**ter **Re**maining was proposed (Gejl et al. (I)). It was developed based on the state-of-the-art indicator *AWaRe* (Boulay et al., 2017). Furthermore, another indicator was developed, namely Distance to Sustainable Conditions (*DSC*), which is similar to *AGWaRe*, albeit in relation to a quantified sustainable abstraction, as discussed later. The indicators developed in this project have different foci, and they can be used individually or in a complementary manner.

Table 1: Indicators for evaluating water use. *WU* is water use, *GWU* is groundwater use, *WR* is water recharge, *EWRs* is environmental water requirements, WF is water footprint, *GF* is groundwater footprint, *GWR* is groundwater recharge and *EGWRs* is environmental groundwater requirements. The measure indicates whether the calculation is based on a relative measure (the share of used water) or an absolute measure (how much water).

	Indicators	Approach	Measure	Considering impacts on	Water resource in focus	References
WTA	$WTA = \frac{WU}{WR}$	Water balance	Relative	Quantitative flows	Surface water	(Alcamo and Henrichs, 2002)
WSI	$WSI = \frac{WU}{WR - EWR}$	Water balance	Relative	Quantitative flows	Surface water	(Smakhtin et al., 2004)
$\mathbf{WSI_{index}}$	$WSI_{index} = \frac{1}{1 + e^{-6.4 \cdot WTA \cdot (\frac{1}{0.01} - 1)}}$	Water balance	Relative	Quantitative flows	Surface water	(Pfister et al., 2009)
Water Footprint	$WF = WF_{blue} + WF_{green} + WF_{grey}$	Quantity	Absolute	Quantitative flows and quality	Surface water and groundwater	(Hoekstra et al., 2009)
Groundwater Footprint	$GF = \frac{WU}{GWR - EGWR}$	Water balance	Relative	Quantitative flows	Groundwater	(Gleeson et al., 2012b)
AWaRe	$AWaRe = \frac{AMD_{world}}{AMD_x}$, $AMD = WR - WU - EWR$	Water balance	Absolute	Quantitative flows	Surface water and groundwater	(Boulay et al., 2017)
AGWaRe	$AGWaRe = \frac{AMD_{ref}}{AMD_{aquifer}}$, $AMD_{aquifer} = GWR - GWU - EGWR$	Water balance	Absolute	Quantitative flows (and possibly quality)	Groundwater	(Gejl et al. (I))
DSC	$DSC = \frac{AMD_{ref}}{AMD_{sus}}$, $AMD_{aquifer} = GWR - GWU - EGWR$	Water balance	Absolute	Quantitative flows and quality	Groundwater	(Gejl et al. (III))

4.1.1. *AWaRe,* an indicator of water impact

To address the need for including impacts on water resources in life cycle assessments (LCAs), a working group within the UNEP-SETAC Life Cycle Initiative, WULCA, had the objective of developing a consensus-based indicator for water use impact assessments (Boulay et al., 2017). The outcome of the project was *AWaRe*, which is a quantification of the relative **A**vailable **Wa**ter **Re**maining per area once the demands of humans and aquatic ecosystems have been met. Whereas earlier indicators (e.g. *WTA* and *WSI*) are based on metrics relative to use, *AWaRe* represents absolute availability per surface unit, which conveys information of how much water is available (Boulay et al., 2017). Hence, it complies with the general understanding that relative water abstraction does not necessarily indicate stress. For example, some areas can easily abstract larger shares of their water without large impacts, because the resource is abundant locally. Conversely, in other places, a small amount of abstracted water can have a large effect. Another modification was that the impact increases in line with increasing consumption until a cut-off point is reached (Boulay et al., 2017). This idea fits well with the general understanding that the closer the combined abstraction is to the upper limit of sustainable abstraction the more severe that abstraction is.

Data for *AWaRe* are conducted on grid cells of 0.5° by 0.5° in size (Schmied et al., 2014) (a geographical coordinate system, which compares to approximately 3025 km^2 near to the equator or approximately 1770 km^2 in Denmark), which is too large to support local challenges, for example where to place a new well field with minimum impacts.

AWaRe is a broad indicator, and it includes both surface water and groundwater. This is interesting for global and overall analyses, for example for mapping impacts related to the production of goods causing impacts at multiple locations across the world. However, when trying to understand the impact of groundwater abstraction from a water utility, *AWaRe* can be somewhat imprecise in terms of local impacts (Gejl et al. (I)).

4.2. Life cycle assessment of water use

With the world becoming more globalised and complex, along with the long-term impacts of human consumption, there is a growing need for systematic, transparent and consistent assessments to evaluate advantages and disadvantages, in order to compare between different options and to guide choices. Sustainability is typically divided into three elements, namely social, economic and environmental, while sustainable development is interpreted as the ability to meet current needs without compromising future needs (Brundtland, 1987). This definition gives guidance on ethics but little assistance on how to prioritise between different options. Within environmental sustainability, LCAs serves as a tool to compare different products, by assessing environmental impacts associated with all stages of a product's life cycle, from raw material extraction through materials processing, manufacture, distribution, use, maintenance and disposal (European Commission, 2010). Recently, LCAs have also been used to compare systems that serve a function, for example stormwater management systems or water supply systems (e.g. Brudler et al., 2016; Godskesen et al., 2012, 2011; Leung et al., 2017). LCAs can help understand and quantify impacts. Due to the original focus on products, attention has rested mainly on energy, chemical consumption and toxic emissions (Berger and Finkbeiner, 2010a). Hence, a development in impact indicators is needed to assess systems and water use. To overcome this hurdle, several system LCAs have included additional impact indicators (e.g. Faist Emmenegger et al., 2011; Faragò et al., 2018; Godskesen et al., 2013). Over the last decade, life cycle impact assessment methods have been developed to include water use effects along with other environmental impact categories, with the LCA framework being adopted in the ISO standard on water foot-printing (ISO 14046 2014).

4.2.1. A frame for linking impacts on the water resources with areas of protection

Water has some characteristics that make it difficult to include in an LCA. First, it fits into several *Areas of Protections* (AoPs) (natural resources, human health and ecosystem quality) and can therefore risk double-counting, since it serves as a resource (e.g. for drinking water), as an environment (e.g. for stream ecology), and when drinking water is polluted or it is too scarce, it can affect human health. Second, both quantity and quality affect water resources and water-dependent environments. As a resource, it exists in all three types of resources: flow, fund and stock. Pradinaud et al. (2018) suggest a framework for including impacts as freshwater resources protection (that affects future generations), as well as short-term impacts that affect the AoP's ecosystem quality and human health directly. Pradinaud et al. also suggest impact pathways linking irreversible changes in freshwater resources to the AoP natural resource and short-term impacts on AoP human health and ecosystems, based on a recovery period duration.

4.3. New indicator for groundwater impact: *AGWaRe*

The *AGWaRe* indicator was proposed in order to assess groundwater impacts (Gejl et al. (I)). It is groundwater-specific and can be applied on smaller scales, and is inspired by *AWaRe* (Boulay et al., 2017). Gejl et al. (III) applied several scales to evaluate *AGWaRe* with median size ranging from 0.25 to 982 km^2.

There is generally an agreement on assessing impacts related only to 'consumptive water use' (Berger and Finkbeiner, 2010b; Hoekstra et al., 2009; Kounina et al., 2012) rather than abstracted water, because sometimes part of the abstracted water is returned within the same catchment area without any alterations to quality and therefore risks double-counting (Jeswani and Azapagic, 2011). This reasoning is valid for surface water, but for groundwater that is discharged in the same catchment area, there can be a large gap in time, and it is therefore not readily available. There are some special cases of groundwater replenishment (Vries, 2020), but these are not used in Denmark. Hence, water abstraction is regarded as *consumptive water use* in these studies.

AGWaRe is based on the parameter $AMD_{aquifer}$ (**A**vailability-**M**inus-**D**emand for the aquifer) compared to a reference *AMD* (Gejl et al. (I)). Similarly to *AWaRe* (Boulay et al., 2017), the reference is chosen to represent the largest scale possible with the data. For *AWaRe*, this is the average global *AMD*, and for *AGWaRe* this is $AMD_{aquifer}$ for Zealand. In accordance with *AWaRe*, the results for *AGWaRe* represent how stressed the studied area is, compared with the reference.

4.3.1. Importance of focusing on groundwater

The different characteristics mentioned in subsection 1.4 herein make it difficult to obtain relevant and precise indicators when combining these water resources, and therefore it is important to have groundwater-specific indicators. Assessing water stress on Zealand with *AWaRe*, the calculated impacts contrast the expected impacts related to water abstraction (Gejl et al. (III)), one reason for which could be that *AWaRe* evaluates the combined impacts on surface water and groundwater.

4.3.2. Scale considerations

Scale is a determining factor for impact assessments, and it should be analysed and harmonised (Boulay et al., 2015; Hybel et al., 2015). Not only will the scale change the quantities of the components, and thereby the results of impact assessments (4.6 Setting boundaries for groundwater impact assessments), but the scale also demonstrates different representations of groundwater behaviour (Figure 3). For example, it affects how the impacts of groundwater abstraction are perceived. Evaluating impacts for a grid scale, the abstraction in a grid cell with little abstraction is not perceived problematic per se. However, if located next to a grid cell where water abstraction is much greater than groundwater recharge, in reality, the groundwater will be 'dragged in' from outside the grid cell, and hence the impact has a larger extent than the impacted grid cell and may affect the area of the grid cell with the small abstraction. On the other hand, evaluating on a large scale, for example river basin or *AWaRe* grids, abstraction will indicate an equal impact within the whole unit, meaning that the calculated effect of water abstraction will influence the groundwater system more than 100 km away.

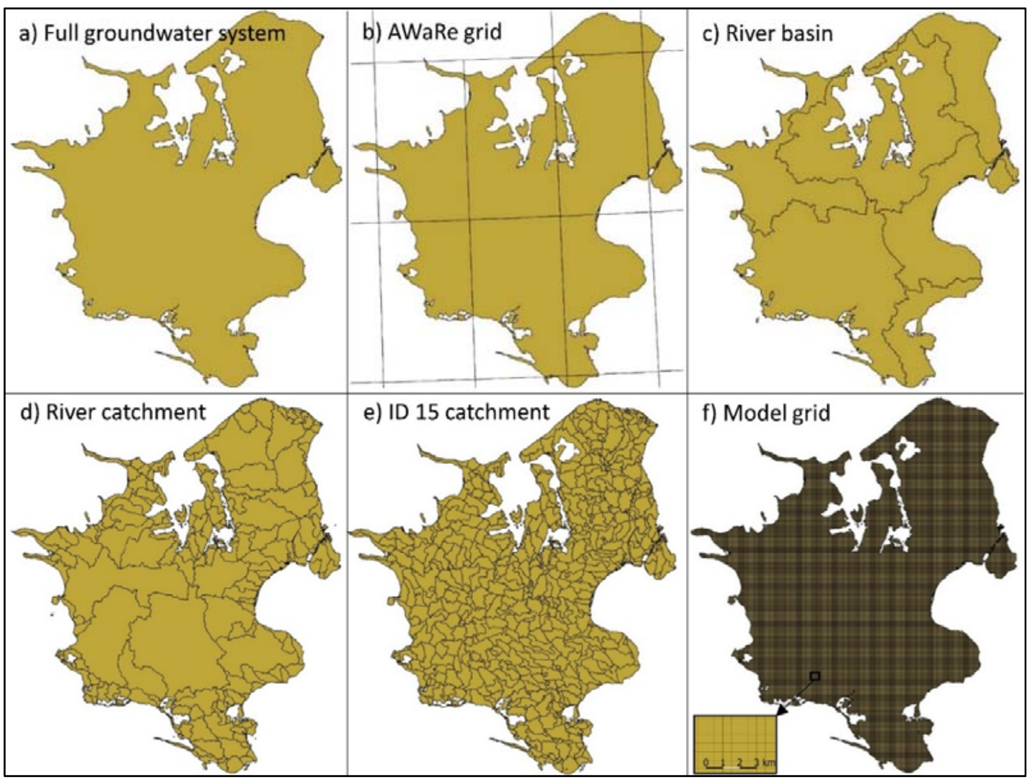

Figure 3: Different scales used to assess water abstraction in Gejl et al. (III), and the *AWaRe* scale (b).

Five consistent scales for assessing water abstraction were used (Gejl et al. (III)), and they were chosen in spite of neither being groundwater specific nor being typically used by utilities, except for when they analyse impacts on surface water. The scales used by utilities for assessing groundwater abstraction are constant in neither time nor space, and they depend on abstraction (e.g.

groundwater catchment area), and for this project it was important that the scales were consistent in this regard.

It is important to choose the scale carefully, and harmonisation thereof is essential for comparing studies. It would be interesting to have a systematic approach for choosing the scale, but to our knowledge this has not been formulated to date. For now, the scale should be chosen based on a discussion of objectives and possibilities. Depending on the objective of the assessment, several different scales and indicators are relevant (Table 2).

Table 2: Goal, scale and indicators for groundwater impact assessments.

Goal	Scale	Indicators
Understand local water availability and stress **Local water management**	Well field/local groundwater demarcation	WTA WSI *AGWaRe* *DSC*
Compare between well fields **Regional water management**	Regional	WTA WSI *AGWaRe* *DSC*
Compare between regions **Prioritise location for production within a nation**	National	WTA WSI *AGWaRe* *DSC* *AWaRe*
Understand stress across global production chains **Prioritise location for production between nations**	International	WTA WSI *AWaRe* Groundwater footprint Water Footprint

One of the objectives was to formulate an impact assessment where the scale could be chosen according to purposes, to ensure the relevance for multiple stakeholders and so that future improvements in groundwater demarcations can be implemented rapidly.

4.3.3. Data needs and limitations

Many of the formerly mentioned impact indicators (e.g. Boulay et al., 2017; Pfister et al., 2009; Smakhtin et al., 2004, Alcamo et al., 2003) are based on global assessments of water use and availability. This provides the advantage of having assessments based on uniform global data, therefore allowing for comparisons. However, many places have invested substantial resources in obtaining an improved understanding of and data on groundwater resources, which are not exploited in these assessments. Moreover, underlying input data have a significant influence on the indicators (Boulay et al., 2015), and therefore it is desirable to use the best available information.

AGWaRe for aquifers on Zealand shows that the scales have a large impact on understanding of water stress (Figure 4). For example, two-thirds of the River basins had a groundwater impact corresponding to at least 50 times the groundwater stress for Zealand in general (Figure 4.a), where for ID15 catchment areas it was on 23% (Figure 4.c).

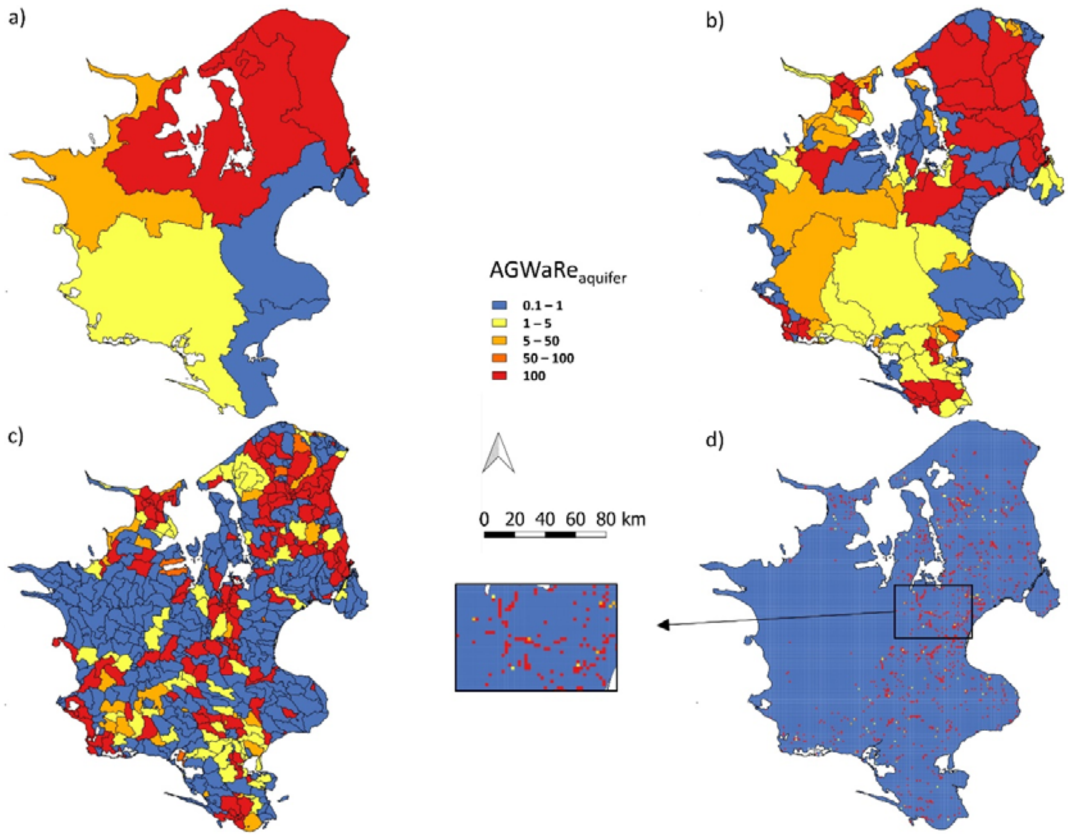

Figure 4: *AGWaRe* for aquifers on different scales on Zealand: a) river basin, b) river catchment, c) ID15 scale and d) model grid. Based on data from Gejl et al. (III).

There are some limitations to *AGWaRe*. First, it requires good groundwater data to give a reasonable assessment. In Denmark, *AGWaRe* can be based on the DK-model, but areas outside Denmark that do not have a similar understanding of groundwater interaction are restricted from applying *AGWaRe*. For example, regions with generally high water consumption and little water availability (e.g. tropical areas) sometimes have scarce data and little understanding of the groundwater resource (Tafesse et al., 2018; *Wu* et al., 2011). Second, accessibility (everyone can perform and evaluate an *AGWaRe*) can potentially result in some unreliable results, if performed without appropriate knowledge and suitable data. This in turn can lead to mistrust in the indicator. Third, the use of diverse data sources complicates comparability. However, knowledge gaps, data gaps and especially diverse data sources and definition are challenges for all water impact indicators.

4.4. New indicator for groundwater impacts: distance to sustainable conditions

The indicator *Distance to Sustainable Conditions* (*DSC*), which relates $AMD_{aquifer}$ to a sustainable $AMD_{aquifer}$, was proposed by Gejl et al. (III). *DSC* is also dependent on scale (Figure 5).

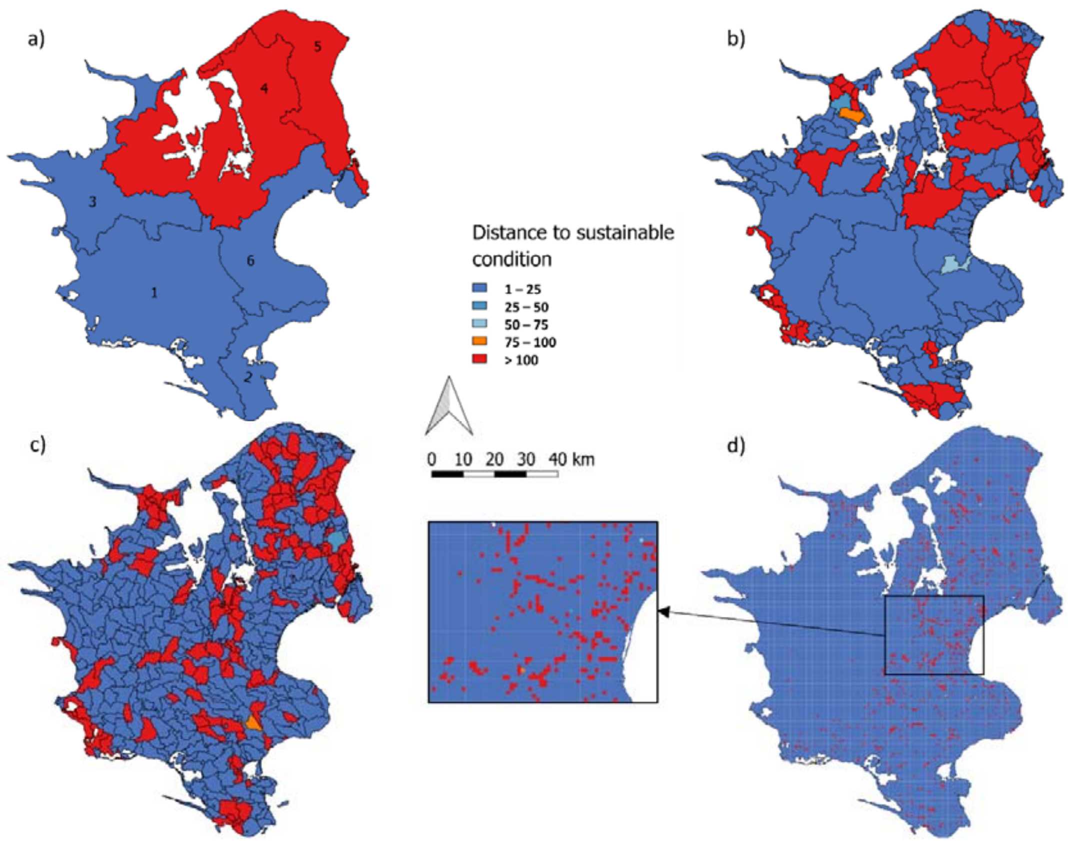

Figure 5: *DSC* for different scales on Zealand: a) river basin, b) river catchment, c) ID15 scale and d) model grid. Sustainable abstraction is found for a maximum allowed drawdown of 3 m in all currently used wells. Based on Gejl et al. (III).

DSC indicates how far the abstraction is away from sustainable abstraction, and it is cut-off below 1 and above 100, with locations where abstraction is higher than the sustainable abstraction (negative values) are assigned the maximum value in this regard. In accordance with *AGWaRe*, *DSC* is defined so that high values indicate high stress, and generally, there is good agreement between *AGWaRe* (Figure 4) and *DSC* (Figure 5).

4.5. Different indicators, different objectives

Different indicators have different objectives. All of the indicators mentioned herein aim at evaluating the impact on water resources, but they differ in their foci: *AWaRe*, *AGWaRe* and *AMD* aim at comparing stress between different locations (Gejl et al. (I)), and *AWaRe* was developed specifically to be integrated into LCAs (Boulay et al., 2017) and therefore relates the studied area to an average of the actual impacts rather than pristine conditions. However, it does not always translate directly to a measure of whether it is sustainable. *DSC* aims to establish an absolute measure of how far the abstraction is away from a sustainable condition and therefore relates to an evaluated sustainable abstraction rather than the actual abstraction (Gejl et al. (III)).

The aim of LCAs is to assess effects on the environment, in order to compare and improve impacts associated with products. Usually, LCAs relate to actual conditions rather than sustainable conditions (Guinée et al., 2001). Parts of the LCA community now suggest relating impacts to sustainable boundaries, or so-called "planetary boundaries" (Bjørn et al., 2015; Bogardi et al., 2013; Gerten et al., 2013). An evaluation of human consumption within planetary boundaries shows that freshwater use is within a 'safe operating space', meaning that there is a low risk of human-induced destabilisation of the earth's system on the planetary scale (Steffen et al., 2015). Planetary boundaries are relevant for some resources; however for water, locally, there are many places with human-induced water scarcity (Haddeland et al., 2014; Unesco and United, 2009). *DSC* is a suggestion for incorporating local sustainable boundaries in the impact assessment.

4.6. Setting boundaries for groundwater impact assessments

In order to obtain reliable indicators that quantify equal impacts, the included parameters should be uniformed and agreed upon, since they influence significantly the outcome of the indicator.

Scale, or spatial resolution, is a determining factor for the outcome of impact assessments (Gejl et al. (I & III)); for example, quantifying *AMD* for grid scale or ID15 scale will influence the perceived extension of the impact (4.3.2 Scale considerations). The choice of geographic scales influences the assessment also, leading to ambiguous conclusions from the quantification of freshwater impacts at local, regional and national levels (Hybel et al., 2015). How the scale influences results is demonstrated in Figure 6 (AMD for model grid & AMD for ID15).

Similarly, the boundary for groundwater recharge is a determining factor in impact assessments (exemplified by *Full groundwater system* & *Limestone Aquifers* in Figure 6). Based on whether one perceives the groundwater resource as the *Full groundwater system* (the water going from unsaturated zone to saturated zone) or as the *Limestone aquifers*, the choice will lead to different quantifications of both groundwater abstraction and recharge (Figure 6). The work in this PhD shows the importance of focusing on aquifers, when possible, to ensure that groundwater availability relates to the groundwater resource.

4.6.1. Groundwater recharge boundary

Groundwater recharge is defined as a vertical flow over a boundary, and three delineations were tested (Gejl et al. (III)):

- GWR_{inf} (net infiltration from an unsaturated to a saturated zone)
- $GWR_{aquifer}$ (recharge to the aquifer)
- $GWR_{net,\ aquifer}$ (net recharge, including both recharge and discharge)

In order to compare between different locations or assessments, it is crucial to have similar *GWR* delineations. Groundwater recharge boundaries can have a decisive effect on the quantification of *GWR*, whereby *GWR* for the actual abstraction differs by a factor 10 and abstraction by less than a factor 2 between the different delineations (Figure 3 in Gejl et al. (III)).

The different delineations each have their advantages. GWR_{inf} boundaries, for instance, are close to the ground and therefore closest to how streams are defined. Hence, the impacts on streams will be most transparent through this definition. $GWR_{aquifer}$ boundaries represent recharges to the aquifer and are therefore closer to indicating how much water is available in the aquifer. $GWR_{net,\ aquifer}$ represents how much water has been recharged to the aquifer, after subtracting groundwater discharges, and so this definition is closer to representing how much water is available for groundwater abstraction after groundwater discharge.

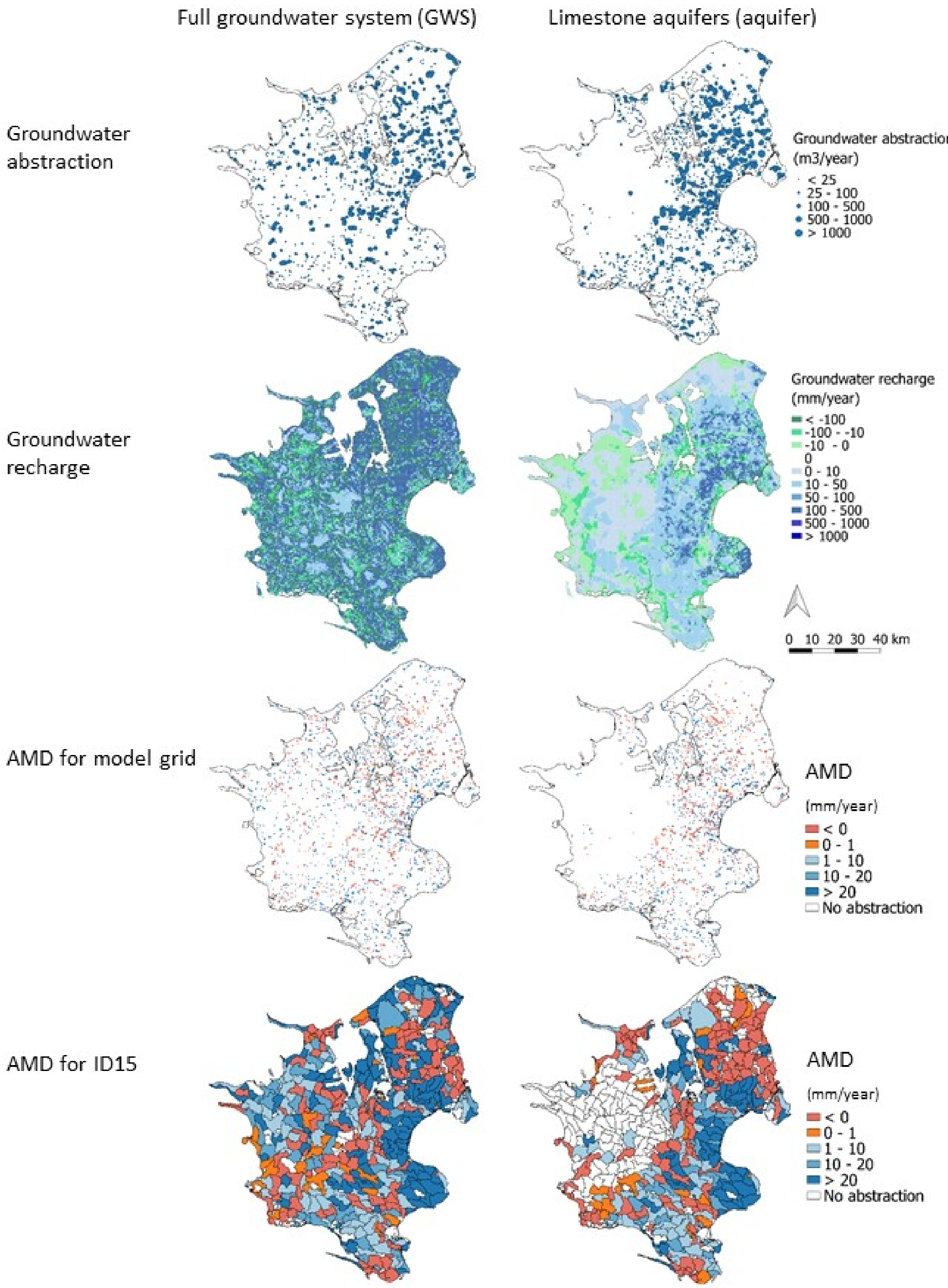

Figure 6: Groundwater abstraction, groundwater recharge and AMD for model grid and ID15 catchment areas for two delineations of the groundwater system: 1) full groundwater system and 2) limestone aquifers. Groundwater abstraction and groundwater recharge are found for actual abstraction (2003-2012), and *AMD* is found for a conditioned drawdown of 3 m in the aquifer. Based on data from Gejl et al. (III).

Since the objective in Gejl et al. (III) was to evaluate impacts in the aquifer related to groundwater abstraction, it was argued that one of the delineations for the aquifer should be applied. Thus, with the intention that the indicator should reflect groundwater availability, $GWR_{net,\ aquifer}$ was used in Gejl et al. (III).

How to set the boundaries of the groundwater system and define the scale in reality is not discussed extensively in the literature, but they are determining for the outcome of the impact assessments. Hence, a discussion about groundwater systems boundaries, in order to ensure uniform parameters and reliable indicators, is recommended.

5. Water quality influenced by groundwater abstraction

Abstraction can change groundwater quality. For example, aquifers in the UK, suffering from long-term abstraction, developed poor-quality groundwater as a result of pyrite oxidation (Kinniburg, Aldous, Oshea 1993). In addition, coastal regions have experienced saltwater intrusion, resulting in a significant deterioration in water quality, for example in Australia, Italy and Libya (Alfarrah et al., 2017; Grassi et al., 2007; Tularam and Krishna, 2009). On the Eskisehir Plain area in Turkey, groundwater did not meet drinking water quality standards, due partly to excessive abstraction causing polluted surface water to infiltrate aquifers (Baba, 2006). Moreover, in aquifers, groundwater abstraction sometimes causes free oxygen in former saturated zones, and the resulting oxidation of pyrite can produce high sulphate concentrations, low pH levels and enhanced heavy metal content, such as Ni, Co, As and Zn (Andersen et al., 2001; Larsen and Postma, 1997).

5.1. Understanding aquifer deterioration from long-term water quality changes

From a utility perspective, water quality affects the suitability of a resource for utilisation, so it is important to ensure stable water quality. Hence, Gejl et al. (II) wanted to go beyond a focus on the quantitative changes of flows and understand how abstraction affects groundwater quality. The hypothesis was that long-term excessive water abstraction will worsen water quality, thus indicating an unsustainable practice. Since groundwater abstraction has different impacts in different places, it was the correlation between drawdown (changes in potentiometric head) and water quality that was investigated (Gejl et al. (II)).

5.1.1. Sulphate as an indicator of aquifer health

Former studies have shown increased sulphate concentrations related to groundwater abstraction (Andersen et al., 2001; Larsen and Postma, 1997). Trends and patterns in abstraction, potentiometric head and water quality parameters were assessed for 28 well fields supplying Copenhagen's water utility, from data spanning from 1900 to 2014. Long time series can give a unique understanding of trends in an aquifer (e.g. Figure 7). Analysing a wide range of water quality parameters allowed us to find the parameter that had the highest correlation with drawdown. For the studied well fields, one water quality parameter stood out, with sulphate concentrations increasing for 25 out of 27 well fields (Gejl et al. (II)). With sulphate clearly responding to drawdown, it is regarded as a relevant indicator for aquifer health in areas similar to those investigated. For other places in Denmark or internationally, it would be interesting to investigate if other parameters are relevant, such as chloride indicating saltwater intrusion (Werner et al., 2012).

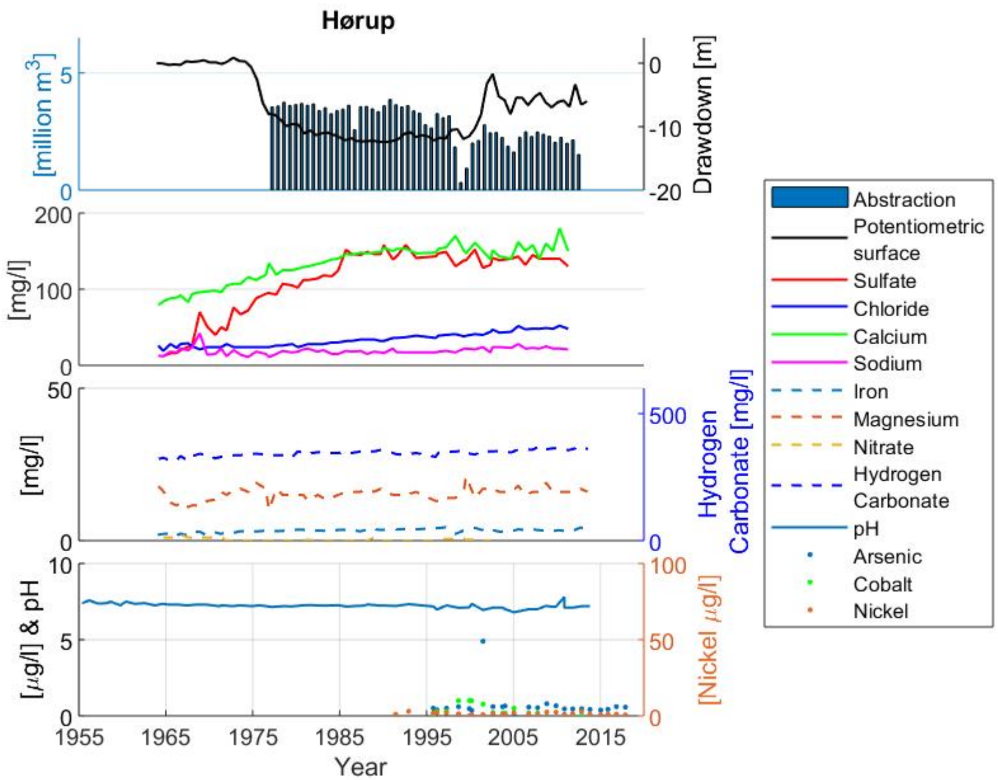

Figure 7: Water quality parameters, plotted with the potentiometric surface and abstraction for the Hørup well field. Based on data from Gejl et al. (II).

Several factors influence sulphate concentrations. For example, to reach levels above background concentrations, there has to be 1) pyrite present in the hydrogeology and 2) oxidisers, which can derive from oxygen or nitrate. Hence, both the hydrogeology and the water quality of the infiltrating water can influence sulphate concentration. If neither pyrite nor oxidisers are present, sulphate concentrations will be low (for example the Æbelholt well field in Gejl et al. (II)). Oxidisers can come from several sources. Nitrate in groundwater can be a by-product from fertilisers. Free oxygen in former saturated zones can be caused by abstraction management in the form of 1) a lowering of the groundwater table above the aquifers (and the produced sulphate is transported downwards with the recharge) and 2) by lowering the groundwater table below the top of the aquifer or by 'windows'. Hence, sulphate concentrations are a consequence of processes not only in the aquifer, but also in the catchment area of the aquifer.

5.1.2. Understanding backward trends provides guidance for future management

In order to understand future conditions in the environment, one can evaluate impacts related to past pressures (Gleeson et al., 2012a; Wada and Bierkens, 2014). Defining continuous changes in water quality as unsustainable, due to a risk that the water quality may not stabilise within a tolerable level, water abstraction before the 1980s, when at its highest alongside drawdown, can be considered unsustainable, because sulphate concentration increased (Gejl et al. (II) and Figure 7). After the 1980s, following a decrease in water abstraction and drawdown, overall sulphate concentrations stabilised or decreased slowly. For Hørup well field, water abstraction decreased at the end of the 1990s, albeit sulphate concentration maybe already stabilised at the end of 1980s at a level of approximately 175 mg/L (Figure 7).

5.1.3. When does a change become an impact?

Part of determining sustainable abstraction involves understanding the nature of unsustainable impacts. In spite of a large spread, there was a correlation between drawdown and increased sulphate concentrations (Figure 8). Gejl et al. (II) evaluated any changes in water quality. Another option could be to evaluate changes greater than a given value, for example 100 mg/l, based on the assumption that abstraction will always result in changes. Only if the changes are severe or water quality is expected to take a long time to return to the original state should the change be regarded as an impact. In Danish utilities, there is a 'rule of thumb' that sulphate concentrations below 100 mg/L can represent a natural change due to abstraction, while sulphate concentrations above 100 mg/L indicate unsustainable abstraction. Finding the correlation between changes in sulphate and drawdown, the fit of the regression was not improved for only considering sulphate concentrations above 100 mg/L (Figure 8). Because we did not find an internationally recognised definition of accepted changes in sulphate concentrations and that analysing only for changes above 100 mg/L did not increase the fit of regression, the analysis in Gejl et al. (II) were based on any changes in sulphate.

This means that any changes in sulphate were included alongside those showing a natural response to groundwater abstraction, without necessarily indicating excessive abstraction. It could be that the sulphate concentration could stabilise at an acceptable value; however, because of the long response periods, there is a risk that the concentration will increase and the resource cannot be utilised for drinking water without treatment. For this reason, the utilities follow developments in water quality parameters and adjust abstraction volumes accordingly, to ensure stable groundwater quality and future water security.

5.1.4. Delay periods

Measured groundwater ages range from months to millions of years upon abstraction (Gleeson et al., 2016). In Denmark, the majority of the abstracted water is older than 20 years (Thorling et al., 2015), and so the long time horizons for groundwater recharge make it difficult to link impacts with stressors. This issue is complicated further by impacts depending also on hydrogeology.

A delayed response to land-use and other actions on land is seen in pesticides (Aisopou et al., 2014), nitrates (Hansen et al., 2011), etc., due to long residence time as well as other effects such as hydrogeology and pumping rates.

A delay in sulphate concentration was observed for 28 well fields (Gejl et al. (II)), some of which experienced maximum sulphate concentration simultaneously to maximum abstraction, whilst others experienced maximum sulphate concentration 20 years after maximum abstraction. This factor increases the complexity involved in understanding how groundwater abstraction affects water quality, because each well field and each compound can have different delay periods. For the studied well fields, the strongest correlation was found for changes in sulphate concentration and drawdown for a 20-year delay period of sulphate response compared to maximum abstraction (Figure 8).

If a similar study were conducted in another place, the results could be different. For example, in Jutland, there is a larger share of groundwater abstraction from unconfined aquifers, which means that the groundwater table is influenced more directly by groundwater abstraction, other influencers, such as precipitation, or a lack of precipitation and surface water interaction (Vainu and Terasmaa, 2016). Unconfined aquifers also have different delay periods, which can be different for different compounds and for different locations, thereby illustrating that a conservative approach should be adopted to ensure future groundwater availability.

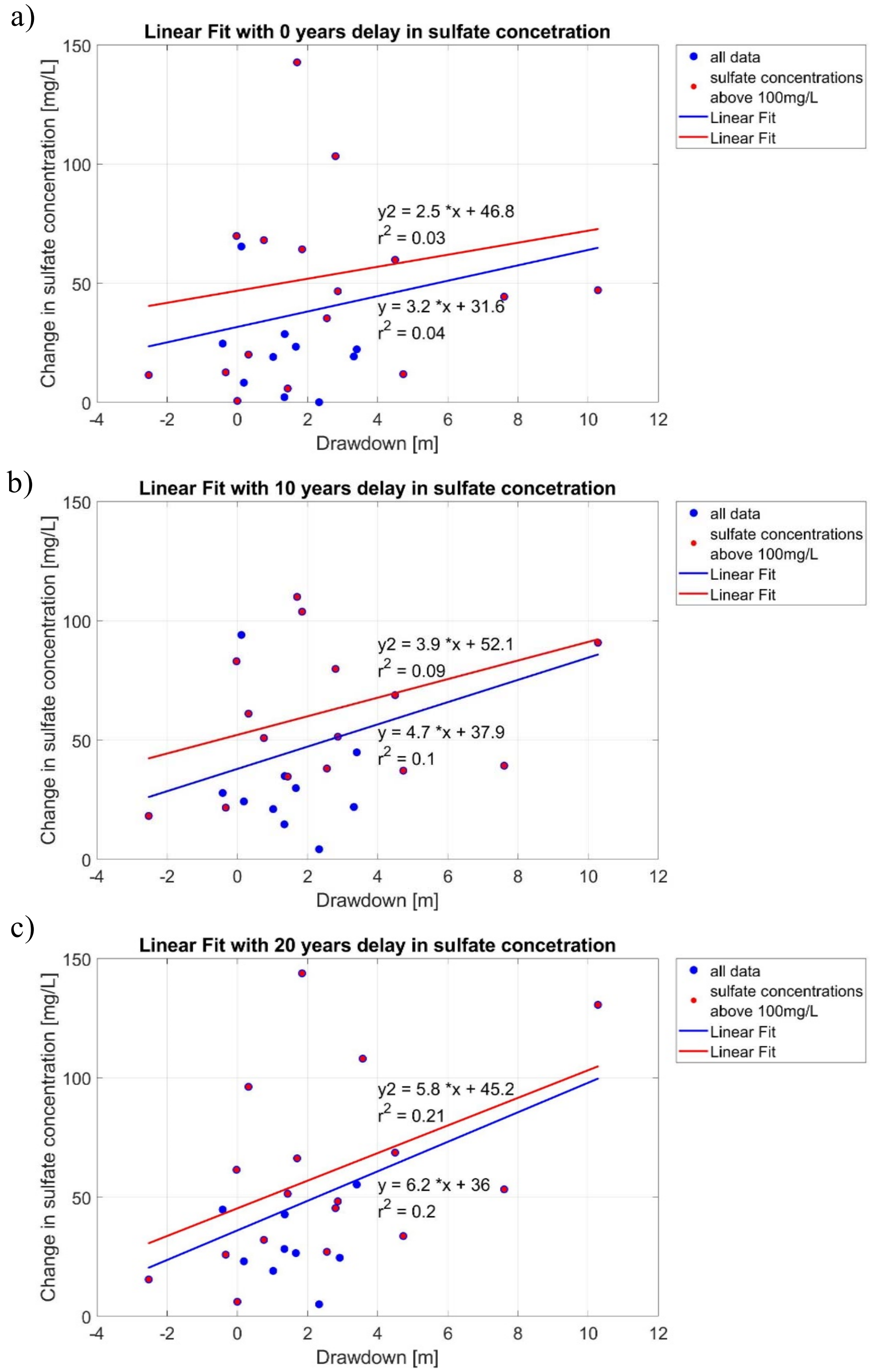

Figure 8: Linear fit of the correlation between drawdown and changes in sulphate concentrations for all data (blue colour) and for sulphate concentrations above 100 mg/L (red) for three different delay periods for sulphate concentrations of a) 0 years, b) 10 years and c) 20 years after maximum abstraction. Drawdown was compared between the first period and the maximum abstraction period. Based on data from Gejl et al. (II).

Several regional groundwater studies provide a 'snapshot' description of water quality conditions over an area at one point in time and influenced by local hydrogeology (for example Postma et al., 2012, 2007). Fewer studies consider changes over time, and even fewer include a statistical analysis of long-term trends (Loftis, 1996). Gejl et al. (II) investigated the correlation between long-term overall changes on a large scale in water quality and drawdown from 1900-2014.

6. Groundwater reserved for environmental needs

Environmental water requirements for ecosystems (*EWRs*) was formulated to ensure that the water for ecosystems was visible and transparent (International River Foundation, 2007), and it has been integrated in impact assessments focusing on surface water. To ensure accordance with *EWRs*, Environmental Groundwater Requirements (*EGWRs*) was formulated with the same objective of securing a proportion of groundwater to sustain ecosystems. To the best of our knowledge, *EGWRs* has not been defined previously, although the concept is already known. Internationally, the concept has been used in different forms; for example, in Australia, focus has been on groundwater-dependent ecosystems and their water demands, by concentrating on shallow groundwater (Doeg et al., 2012). Another example is a study of the exploitation of global aquifers, where *EGWRs* was included to ensure environmental flows by setting the measure high enough to sustain Q_{90} in streams, i.e. monthly streamflow that was exceeded 90% of the time compared to a reference period (Gleeson and Wada, 2013). These methods examined flows in streams and systems near the earth's surface. In Danish water management plans, groundwater abstraction was evaluated compared to a percentage of groundwater recharge (Henriksen et al., 2008), with the intention to preserve both aquifer health and stream flows (Henriksen and Refsgaard, 2013). A recent indicator has evaluated how groundwater abstraction affects ecological flow from a set of physical parameters (Graeber et al., 2015). This indicator is closer to actual impacts in streams; however, it only considers instream ecological flow requirements and not groundwater-surface water interactions or quality.

EGWRs was defined as "*water from groundwater resources needed to sustain flows, preserve groundwater dependent ecosystems and maintain good groundwater quality*" in accordance with *EWRs*, albeit applied to groundwater aquifers (Gejl et al. (II)).

6.1. Water quality-based environmental groundwater requirements vs. flow-based environmental groundwater requirements

Since impacts on ecosystems are related to both flow in streams and water quality in aquifers (Gejl et al. (II)), it was recommended to divide *EGWRs*, as illustrated in (Figure 9):

- $EGWR_{flow}$: Groundwater reserved to sustain base flow in streams and groundwater-dependent ecosystems (above ground)
- $EGWR_{wq}$: Groundwater reserved to sustain aquifer health related to water quality affected by water abstraction in the aquifer (below ground)

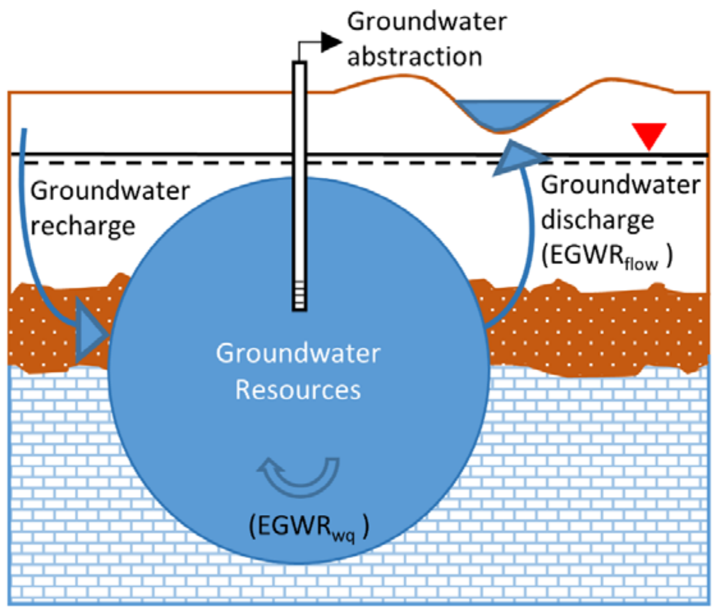

Figure 9: Conceptual figure of groundwater resources and their interaction with groundwater recharge (*GWR*), groundwater abstraction, $EGWR_{wq}$ and $EGWR_{flow}$

In the Danish River Basin Management Plans, *EGWRs* was included as 30% of groundwater recharge, including considerations of both types of *EGWRs* (Henriksen and Refsgaard, 2013). This assumption was verified for Zealand (Henriksen et al., 2008) and applied to the whole of Denmark as an indication of groundwater stress. Groundwater recharge differed greatly around the country and thereby also *EGWRs* (because it is set as a part of groundwater recharge). In reality, the water levels needed for ecosystems are determined by parameters other than groundwater recharge, e.g. the vulnerability of an ecosystem or the importance of high flows at certain times for fish to breed.

$EGWR_{wq}$ was evaluated based on a maximum allowed drawdown in the aquifers (Gejl, et al. (III)). The correlation between water quality and drawdown (Gejl et al. (II)) induced the assumption that keeping drawdown within a certain limit would generally ensure stable water quality. In the following, $EGWR_{wq}$ was ensured by a conditioned drawdown of 3 m.

Safe groundwater yield has been modelled to avoid saltwater intrusion (Ahmed et al., 2018) as a share of groundwater recharge (Henriksen and Refsgaard, 2013) and to ensure sustainable water quality in aquifers (Gejl et al. (III)).

6.1.1. $EGWR_{flow}$ and $EGWR_{wq}$

In the following, $EGWR_{flow}$ and $EGWR_{wq}$ will be compared for Zealand.

Table 2: Scenarios used in Gejl et al. (III). Abstraction$_{wq}$ is the maximum abstraction complying with $EGWR_{wq}$.

Scenarios	Pristine	Actual abstraction (2003-2012)	Abstraction$_{wq}$
Abstraction (million m^3/year)	0	157	261

Using the three scenarios in Table 2, average modelled daily flows at 634 river stations were analysed (Table 3). For pristine conditions (simulating no abstraction), flow in the streams differed from 0.001 to 7.2 m^3/s with an average and a median flow of 0.43 m^3/s and 0.08 m^3/s, respectively. For the actual abstraction, the median flow for all stream stations decreased by 9% compared to pristine conditions. For abstraction$_{wq}$, the median flow decreased by a further 5%. In absolute values, actual abstraction decreased the flow by 0.01 m^3/s, and the abstraction$_{wq}$ decreased the flow by 0.02 m^3/s.

Table 3: Average daily flows for 634 river stations, from 2003-2012. Obs. The maximum and minimum flows are not at the same stream stations for the different scenarios. The minimum modelled flow is 0.001, and therefore the model cannot represent changes in low flows. Abstraction$_{wq}$ is the maximum abstraction complying with $EGWR_{wq}$.

	Pristine flow (m3/s)	Actual abstraction (m3/s) (change from pristine flow)	Abstraction$_{wq}$ (m3/s) (change from of pristine flow)
Average	0.43	0.39 (-10%)	0.38 (-13%)
Median	0.08	0.07 (-9%)	0.06 (-14%)
Maximum flow	6.6	6.1 (-7%)	6.0 (-10%)
Minimum flow	0.001	0.001 (0%)	0.001 (0%)

How the flow responds to abstraction depends on local conditions at the stream station, such as proximity to a well field. There are stations where the flow is hardly influenced by actual abstraction or by abstraction$_{wq}$ (Figure 10.a). Some stream stations show the largest decrease in average daily flow due to abstraction$_{wq}$ (Figure 10.c), whilst others stations show the same result due to actual abstraction (Figure 10.b and Figure 10.d).

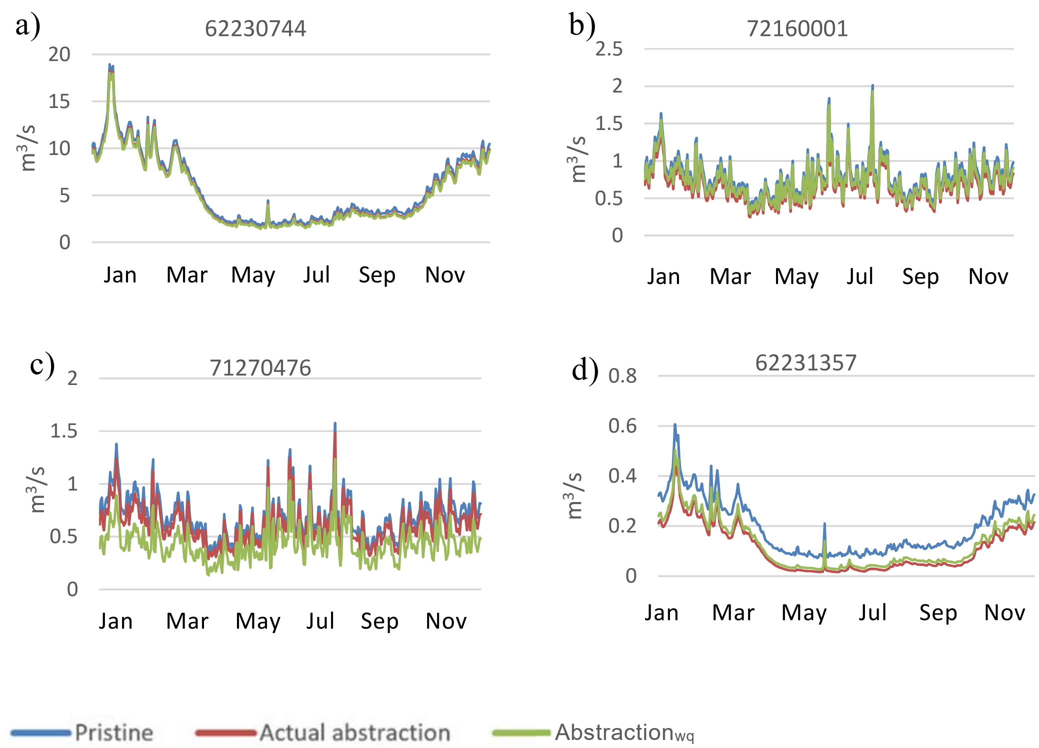

Figure 10: Examples of the modelled average daily flow for four stream stations for pristine conditions, actual abstraction and abstraction$_{wq}$. The locations of the stations can be seen in SI 1. Please note different scales on y-axis.

Simple presumptive standards were applied to understand the impact on the streams' ecosystems (Richter et al., 2012). The idea is to analyse the altered flow compared to maximum allowed alterations from pristine conditions. There are different suggestions for maximum allowed alterations to sustain a sustainable stream ecology (Richter et al., 2012). For example, in the UK, a technical advisory group suggested different tolerances to flow alteration across taxa groups, where a 10% flow alteration was regarded as likely to have a negligible effect for most taxa, stream types and hydrological conditions (Acreman and Ferguson, 2010). The method proposed by Richter et al. (2012) is only intended for application where detailed scientific assessments of environmental flow needs cannot be undertaken within near time. However, it does provide a quick indication of possible impacts, without ignoring the importance of a differentiated flow throughout the year. Applying 10% of pristine conditions as $EGWR_{flow}$, it is notable that abstraction$_{wq}$ results in more days where the flow does not comply with $EGWR_{flow}$ than the actual abstraction (Table 4). For example, actual abstraction leads to a reduced flow by more than 10% from pristine conditions at 495 out of 634 stream stations for a minimum one day in the period 2003-2012, where abstraction$_{wq}$ led to a reduced flow of more than 10% at 546 stream stations for a minimum of one day. Actual abstraction led to a reduced flow of more than 10% for the whole period at 10 stream stations, and for abstraction$_{wq}$ it was for 21 stream stations.

Table 4: No. of stream stations with a daily flow outside the sustainable boundaries of pristine flows. Daily flows are found for 634 river stations.

Period	**2003-2012**	
Scenario	Actual abstraction	Abstraction$_{wq}$
More than 1 day	495	546
More than 30 days	380	479
The whole period	10	21

At some locations, the enforcement of $EGWR_{wq}$ would lead to reduced abstraction compared to actual abstraction (Gejl, et al. (III)), which is probably near to some of the stream stations where actual abstraction led to a more reduced flow than abstraction$_{wq}$ (Figures 10.b and 10.d). Furthermore, due to differences in flow over the course of a year, $EGWR_{flow}$ will set larger limitations in the summer than in winter, although the protection of aquifers does not necessarily follow the same variations over any given year. Hence, it is important to assess both $EGWR_{wq}$ and $EGWR_{flow}$ and variations over the year, to ensure stream ecology and stable groundwater quality.

$EGWR_{wq}$ and $EGWR_{flow}$ protect different environmental needs which in turn sustain different ecosystem functions. It differs between the stream stations which one of two that are larger (Table 4). Neither of these options is constantly greater than the other, and therefore none of them can solely constitute the assessment of water needed for the environment.

Table 5: Comparing $EGWR_{flow}$ and $EGWR_{wq}$ for 634 stream stations in the period 2003-2012.

	No. of stream stations
$EGWR_{flow} > EGWR_{wq}$ for the whole period	87
$EGWR_{flow} < EGWR_{wq}$ for the whole period	21
Average $EGWR_{flow}$ > average $EGWR_{wq}$	374
Average $EGWR_{flow}$ < average $EGWR_{wq}$	260

7. Suggestions for application

The groundwater impact assessment and evaluations detailed herein can guide utilities and other stakeholders in their work towards sustainable groundwater abstraction. Below are some suggestions of where they may contribute.

7.1. What this PhD work can contribute to water utilities

Utilities around Denmark and the world can apply one or several of the methods, to evaluate their groundwater abstraction. Furthermore, they can use the findings to assist future planning and prioritisation between locations of new well fields. Utilities need to optimise and economise their water abstraction approaches, and therefore they need to be more efficient while minimising their impacts. Therefore, it is suggested that water utilities implement *AMD*, *AGWaRe* or *DSC* to ensure awareness of impacts related to different options in the planning of water abstraction, for example when they need to prioritise between options in relation to meeting demand. Furthermore, the findings on the correlation between long-term drawdowns and changes in water quality could increase awareness of the importance of securing a stable groundwater table, in order to sustain long-term quality, thus ensuring future water abstraction and long-term investments. The suggested method, i.e. to apply conditioned drawdown, shows the possibilities of including impacts related to water quality in the management of groundwater abstraction. Furthermore, an accepted method for quantifying groundwater impacts could play a role in justifying additional costs related to challenging resource conditions.

7.2. What this PhD work can contribute to other stakeholders

AMD can be used as a characterisation factor in local challenges where *AWaRe* cannot assist. It can be implemented in the frame set up to include impacts on the water resource in LCAs for local assessments (Pradinaud et al., 2018).

In Denmark, GEUS could allow for the easy extraction of the data needed to perform *AMD*, *AGWaRe* and *DSC* and implement them in their contributions to national analyses, for example the River Basin Management Plans (SVANA, 2016). In this way, the indicators could be applied easily in new investigations and allow for including groundwater impacts in public evaluations of abstraction. Furthermore, assessing sustainable abstraction based on conditioned drawdowns rather than from a share of the groundwater recharge could support continuous work on evaluating sustainable groundwater abstraction.

In addition, the association of Danish utilities, DANVA, could consider incorporating one or more of the suggested impact assessments mentioned herein in their benchmarking of water utilities. In this way, water utilities would be compared based not only on minor impacts such as price, carbon footprint, leakage, etc. (DANVA, 2018), but also on impacts on their main resource use. The method is ready to be applied, albeit further discussions are needed to ensure uniform scales and parameter boundaries.

8. Conclusions

This PhD developed a number of initiatives on the way toward improving groundwater impacts that are relevant for water utilities. In summary:

- A groundwater impact indicator, *AGWaRe*, was developed to highlight local groundwater stress. In short, it:
    - Builds on existing state-of-the-art principles for LCA water stress impact assessments.
    - Allows for understanding water stress on a scale smaller than national or regional assessments, which is crucial for water utilities and other stakeholders.
- The correlation between long-term drawdown and water quality was evaluated, and for the analysed well fields supplying water for Copenhagen, Denmark, it was found that:
    - Sulphate is a good parameter for indicating excessive groundwater abstraction.
    - In spite of the correlation between drawdown and change in sulphate concentrations being spread out, it is statistically significant.
    - Indications of abstractions before the 1980s were unsustainable, which could assist in planning future sustainable groundwater abstraction.
- A new method for evaluating sustainable groundwater abstraction was suggested, based on conditioned drawdown. It was found that:
    - Overall actual water abstraction on Zealand is within sustainable abstraction limits in relation to aquifer health; however, the abstraction should be redistributed, since the actual abstractions pose a risk of resulting in changed water quality locally.
    - The scale and delineation of groundwater resources are determining factors for the outcome of the assessment.
    - It was possible to quantify $EGWR_{wq}$.

Furthermore, a definition of $EGWR_{wq}$ was suggested. There are several proposals on how to apply these findings, as well as indicators on how to manage the distribution of groundwater abstraction. The indicators, methods and evaluations in this thesis are a step toward obtaining tools based on actual impacts, which in turn could help utilities in achieving sustainable resource utilisation.

9. Perspectives: future research and recommendations

This PhD shows the importance of continuing to work towards sustainable groundwater abstraction and improving our understanding of what this means in reality.

9.1. Significance of this PhD work

This work demonstrates that there is still some effort required, in order to obtain reliable, accepted indicators representing accurate impacts on the groundwater resource, while the general focus on global, overall assessments poses the risk of misrepresenting actual local impacts.

This work also shows that the development of locally adapted impact assessments is possible, but further work is needed to define an accepted, relevant and consistent scale.

9.2. Suggestions for future research

Assessing the impacts of groundwater abstraction is a complex task. This study offers the first steps towards advancing indicators on a local scale, including a new understanding of how underground ecosystems are affected by groundwater abstraction. However, further elaboration in this field is needed to ensure transparent, reliable and generally accepted indicators. For example, it is suggested:

- To work on securing comparability between studies including groundwater impacts. This can be done if $AMD_{aquifer}$ or *DSC* are used. However, to serve as indicators, further work is needed to classify $AMD_{aquifer}$ or *DSC* in categories that suggest stress levels.
- To develop a systematic method for choosing the scale. To ensure comparability, it is important that studies have similar scales and a method that will ensure harmonisation.
- To broaden the understanding of the impacts on aquifer health related to abstraction. Additional studies on how groundwater quality responds to its abstraction in other places in Denmark and around the world would increase the relevance of $EGWR_{wq}$. Additionally, it would also broaden the applicability of the conditioned drawdown to groundwater systems with other challenges.

- To develop *AMD* so that it can be applied in other locations with less data. Many water-scarce areas lack reliable, local data, and yet they are in need of accurate assessments of groundwater abstraction.

- To investigate the potential of using alternative global data for quantifying components of the groundwater impact indicators. Currently, substantial efforts are being put into remote sensing, and it would be interesting to investigate if these data can verify or improve estimations of data areas where it is difficult to obtain precise quantifications of the groundwater recharge (Rashid and Ahmed, 2018; Richey, 2015; *Wu* et al., 2019).

- To investigate patterns of well fields that respond with deteriorating water quality to groundwater abstraction. There were larger differences in the responses to drawdown between the studied well fields in Gejl et al. (II), and it could be interesting to explore if there is a pattern for those aquifers where water quality responds most excessively to drawdown. Similarly, it would be interesting to establish if there are patterns for aquifers that have modest responses in water quality to drawdown.

- To evaluate positive side effects from groundwater abstraction, e.g. reduced risk of flooding, which is already a concern for water utilities in Denmark, which sometimes continue groundwater abstraction, without utilising the abstracted water, in order to reduce the risk of water in cellars. Since modern societies are built based on long-term lowered groundwater tables, it can have extensive societal impacts to return to pristine conditions. To understand fully the impacts, positive aspects or avoided impacts should be included in order to compare options fairly. This is consistent with standard LCA procedures (Weidema et al., 2004).

- To consider changes in the climate in terms of more extreme weather and changes in groundwater recharge, discharge, storage, saltwater intrusion, transport, etc. (Shahid et al., 2017; Taylor et al., 2013). Quantifying the impacts, however, is difficult due to uncertainties in climate projections and the responses of hydrological systems to climate variability.

- To explore how implementations of conditioned drawdown can be modelled for other areas/geologies etc.

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11. Appendices

11.1. Location of stream stations

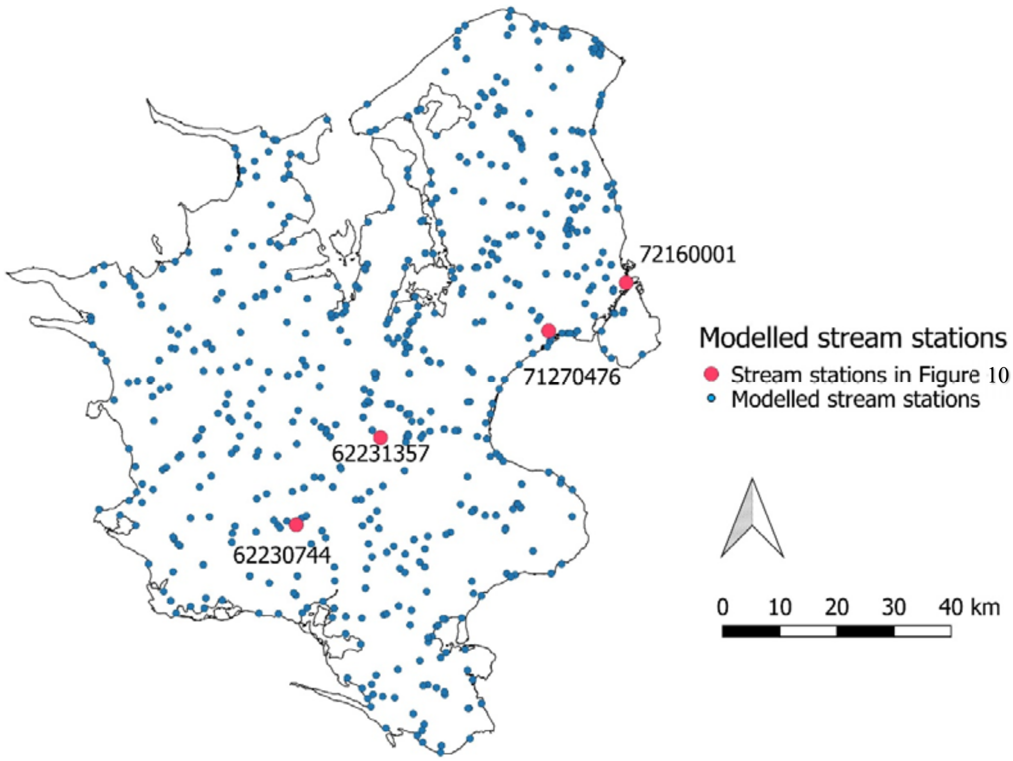

Figure 11: The locations of modelled stream stations and the four stations presented in figure 10.

The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within five sections: Air, Land and Water Resources, Urban Water Systems, Water Technology, Residual Resource Engineering, Environmental Fate and Effect of Chemicals. The department dates back to 1865, where Ludvig August Colding gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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